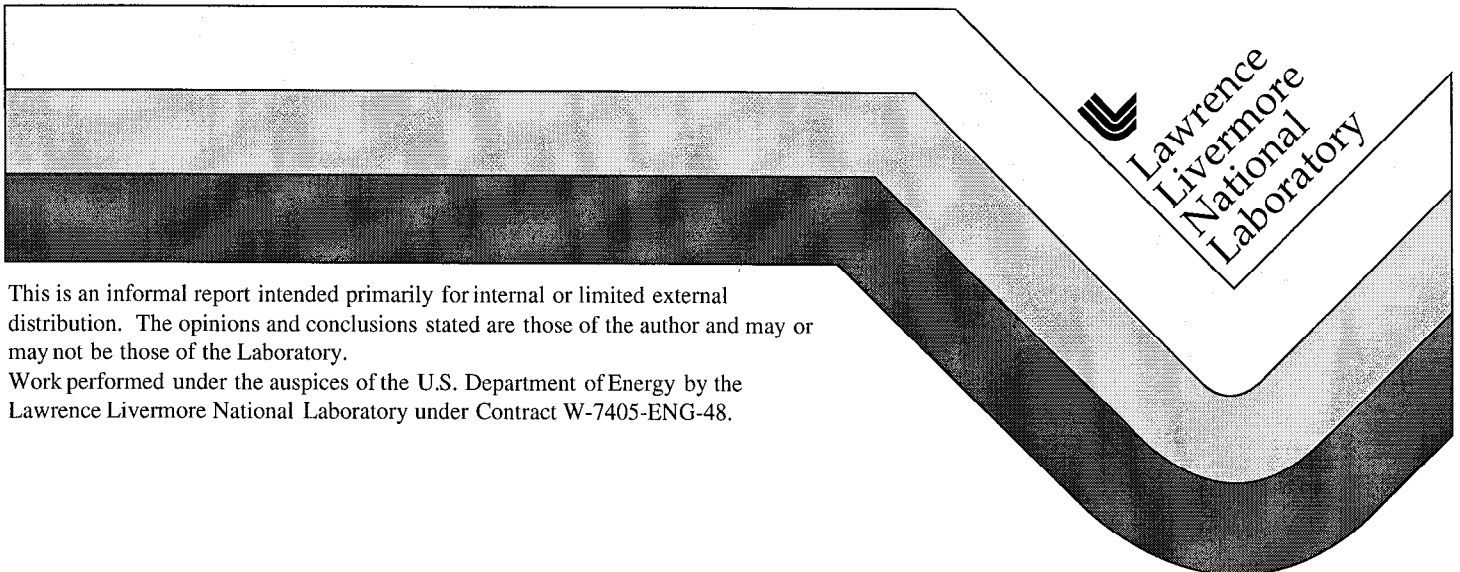


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The Comprehensive Nuclear-Test-Ban Treaty (CTBT), which was signed in 1996 and still needs to be ratified by the United States, forbids all nuclear tests and creates an international monitoring system (IMS) to search for evidence of clandestine nuclear explosions. As specified in the treaty, the IMS will consist of 170 seismic stations that record underground elastic waves, 60 infrasound stations to record low-frequency sound waves in the air, 11 hydroacoustic stations to record underwater sound waves, and 80 radionuclide stations to record airborne radionuclide gases or particles. The International Data Center (IDC), located in Vienna, receives data from the IMS system and applies standard event screening criteria to any detected events with the objective of characterizing and highlighting events considered to be consistent with natural phenomena or a non-nuclear man made phenomena. The National Data Center (NDC) for each country must go a step further than the IDC and identify events as consistent with natural phenomena, non-nuclear manmade phenomena, or a banned nuclear test using these monitoring technologies.

The United States NDC (USNDC) is responsible for American monitoring of the treaty. In their role, the USNDC is developing an automated process, or pipeline, that detects, locates, and discriminates incoming events. Following this automated process, trained analysts work to further refine the events and communicate the technical analysis to the U.S. National Authorities. At Lawrence Livermore National Laboratory (LLNL), we are working to aid the NDC in their pipeline and analyst review by helping to calibrate IMS seismic stations and supporting networks that are in the Middle East, North Africa, and portions of the FSU. Our primary mission is to enhance the monitoring network's ability to accurately detect, locate and identify explosions that may occur underground or in the oceans to meet monitoring goals. Through the DOE CTBT R&D program, in coordination with Los Alamos National Laboratory, Sandia National Laboratory, and Pacific Northwest National Laboratory, we are developing a comprehensive framework of data, models and algorithms to achieve this goal. The core of our framework is the Livermore end-to-end statistical model that propagates the primary errors through the automated analysis and accurately quantifies our technical uncertainties for the policy, or decision maker.

The Challenge: Regional Calibration

Regionalization has become the key challenge of the Comprehensive Test Ban Treaty (Figure 1). Under the Threshold Test Ban Treaty, explosions above 150 kt are banned and need to be identified. Such large explosions typically have seismic magnitudes of about 6 or greater. Energy from these events travels through the Earth's relatively homogeneous core and mantle and is easily picked up by numerous teleseismic (distances greater than 2000 km) stations. Given the simplicity of the seismic paths, the seismograms are relatively simple and the analysis of these events is usually straightforward. On the other hand, under the CTBT one must now determine that a nuclear explosion, no matter what its size, took place and pinpoint its location accurately which requires monitoring to magnitudes 3.5 or less. Given the small size of these events, they typically are only recorded at closer regional (distances less than 2000 km) stations. Energy from these small events travels through the Earth's complex crust and upper mantle and are typically picked

up on only a sparse set of nearby stations. Given the complexity of the crust, the seismograms are quite complex and the nature of event's seismic waves can vary dramatically over relatively short distances of propagation. In addition, the logarithmic relation between seismicity and event size means that natural earthquakes are at least two orders of magnitude more frequent at smaller magnitudes and, thus, will compose the majority of events analyzed under a CTBT.

We are developing a DOE R&D Knowledge Base (KB) as our primary product which is for the USNDC. This KB characterizes seismic travel-time and amplitude fluctuations for energy propagating from these smaller events, through the crust and upper mantle, to surrounding seismic stations.

Location and Identification Efforts

The CTBT R&D effort at Livermore seeks to accurately locate and identify potential clandestine nuclear explosions based on seismic signatures. The location effort utilizes the time it takes pressure and shear waves to travel from a seismic event, through the earth, to a set of recording seismic stations. The identification effort goes one step further and seeks to identify nuclear explosions based on amplitudes and frequency content of phases.

To account for variations in regional structure, we are developing a comprehensive framework that accounts for dramatic variations in travel-times and amplitudes that occur over relatively short distances in the crust - variations that can lead to significant errors in event location and identification. Figure 2 gives a general overview of how we accurately account for these errors. We begin by cataloging well constrained - both in location and source characteristics - historic earthquakes and explosions in the DOE KB and use these events to spatially map their amplitude and travel-time changes as a function of geographic coordinate. We then use this information to refine our models of the earth's velocity structure. These refined models can then be used to account for the travel-time and amplitude fluctuations when a potential clandestine nuclear test occurs. As more events occur over time, the velocity models are continually refined and our ability to account for crustal effects is improved. However, one quickly realizes that model prediction will never be perfect. By its very nature, a model of the earth is underdetermined by the observational data and, thus, gives only an average estimate of the true earth structure. More precisely, if one tried to predict the travel-time or amplitude of an event that was used to develop the model, one could not recover its exact characteristics. To provide an accurate characterization, we have developed a set of innovative statistical techniques and algorithms that work together with the model to empirically predict the travel-time or amplitude correction.

At the heart of our approach is the nonstationary Bayesian kriging (NBK) technique. This technique accounts for the nonstationarities in the correction surface that exist between geophysically distinct regions and allows for the introduction of the tomography models through *an a priori* distribution. In addition, this technique allows for interpolation and extrapolation and provides robust error estimates in the predictions. Using this technique, we have demonstrated that we can provide the full correction when a new event is co-located with a historic event in the region. In the case that the new event is not co-located, but instead is located near a set of historic events, we can provide a robust estimate of the event correction based on interpolation or extrapolation of the nearby events. To date, all

comparison studies at Livermore and Los Alamos have shown that the model combined with NBK approach outperforms other conventional approaches.

We have demonstrated the benefit of this calibration framework using accurately located aftershock sequences and well constrained explosions at former nuclear test sites (Figures 3 and 4). Using what we have learned from these focused studies, we have been applying this capability to broad areas of the North Africa, the Middle East and the former Soviet Union. More specifically, we have developed and refined a procedure which involves a number of specific steps, including: 1) collecting all available seismic data; 2) defining geophysical boundaries where propagation characteristics change abruptly; 3) using collected seismic data to develop refined 3D tomographic models of the earth's crustal and upper mantle structure; 4) calibrating the magnitude scale; 5) applying magnitude and distance corrections; 6) determining detection capability for each seismic phase; 7) evaluating and optimizing seismic location and identification measures, and 8) establishing independent source information to avoid circularity in testing location and identification performance. Although each step in this calibration procedure requires much effort, once calibrated, we integrate all the information into a station correction surface using a modified form of kriging to interpolate and extrapolate corrections to a new event of interest.

Looking to the Future

The Department of Energy effort is entering a new phase where field calibration projects are becoming more critical to its CTBT mission. As discussed above, we have collected the majority of easily available over-the-internet historic data in the Middle East, North Africa and the former Soviet Union and are incorporating much of these into our current calibrations. As this work is completed the primary improvements to monitoring will come from the installation of stations and the realization of dedicated calibration experiments. Station installations may include new IMS stations coming on line and other supporting stations that may further enhance the IMS network. Calibration experiments include controlled explosions where the location, origin time, and source characteristics are well known. Experiments can also include the careful monitoring of known mining areas or the deployment of stations to better constrain the crustal structure in a region. Given such a broad variety of calibration opportunities and a limited level of funding, it is essential that we provide an objective tool to plan and, thus, prioritize future station installation and calibration experiments based on their combined benefit and cost.

In response to this need, we have utilized our framework above to develop a planning tool. This planning tool draws on the entire CTBT R&D KB and can accurately reflect our current state of the art techniques, algorithms, and calibrations. In the location case, we evaluate capability by synthetically generating the travel-times for seismic events spanning a given region. We do this by utilizing our best estimate of picking and model error processes. We then relocate these events and estimate the location uncertainty across the entire region as shown in Figure 5. In the identification case, we evaluate capability by mapping the number of suspicious events that need to be reported under assumptions of a specific magnitude threshold and missed violation confidence. As an added benefit this tool allows us to objectively measure and report progress to our sponsor as we proceed. With these tools in hand and with our effort in the continued development of new innovative techniques in location and identification, we feel that we are well poised to meet our mission goals in the year 2000 and beyond.